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TECHNICAL REPORT ARCCB-TR-01026

COATINGS EVALUATION USING A VENTED COMBUSTOR

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DECEMBER 2001

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
December 2001

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
COATINGS EVALUATION USING A VENTED COMBUSTOR

5. FUNDING NUMBERS
AMCMS No. 6226.24.H180.0
PRON No. TU1A1F261ABJ

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, AMSTA-AR-CCB-O
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER
ARCCB-TR-01026

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Submitted to Society for Experimental Mechanics, Inc. *Experimental Techniques.*

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Characterization of protective coatings in their development stages is a costly process. This report will focus on an experimental, economic, subscale method used to compare the suitability of several candidate gun tube bore coatings. The report addresses a methodology to effectively evaluate coatings in the environment of a vented combustor. Although the discussion is specific to damage caused by propellant combustion, the test procedure can be used to discern the integrity of protective coatings used in applications other than armament systems.

14. SUBJECT TERMS
Vented Combustor, High Contractile Chromium,
Erosion, Laser Surface Alloying

15. NUMBER OF PAGES
11

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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ACKNOWLEDGMENTS

The authors would like to thank senior researchers Dr. Paul Cote, Mr. John Underwood, and Mr. Mark Witherell for their guidance in various phases of this work, and also Mr. Christopher Rickard for his metallographic assistance.

INTRODUCTION

The service life of modern day large caliber gun tubes is generally a function of the effectiveness of the bore coating. There are two primary factors in determining the safe service life in such an application, which really represents a pressure vessel: a predetermined safe service fatigue life (i.e., number of rounds fired), and an acceptable depth of erosion. Application of a protective coating to the bore of the gun tube aids in the reduction of bore erosion. However, coating application processes may reduce fatigue life for any of several reasons, which are discussed below. The current industry standard for bore surface protection is the electrodeposition of high contractile (HC) chromium, also known as "hard chrome." The characteristics of chromium offer excellent wear resistance due to the metal's high hardness and excellent thermal and oxidation resistance due to the metal's high melting point of 1907°C (3465°F) and oxide-metal volume ratio of 1.99 (ref 1). Nevertheless, electroplated chromium undergoes a contraction when heated causing it to crack, which typically leads to excessive spalling or flaking, when subjected to high thermal and/or mechanical stresses. The initial cracks in the chromium also act as stress concentrators, thus resulting in a reduction of fatigue life. Once the chromium layer is removed, the underlying steel substrate becomes exposed and results in rapid material degradation within the aggressive environment of hot, high velocity, high pressure, often chemically aggressive gases and particulate material.

There is extensive ongoing work to identify new coating materials and techniques for characterizing various coating systems to further increase tube erosion life. A significant gap exists in determining coating response to environmental conditions, hence the need for an economic subscale test method. This report will discuss recent work using a vented combustor as a subscale means of exposing experimental coatings to propellant combustion temperatures and byproducts.

EXPERIMENTAL METHOD

The vented combustor used for this testing is capable of operating at pressures as high as 415 MPa (60 Ksi). A nozzle/orifice combination, backed by a burst disk, is used as the method of exposing the coating to the environment. A predetermined propellant mass is placed in the chamber and ignited. The maximum pressure achieved is dependent on the material and thickness of the burst disk and the amount of propellant used. Upon combustion of the propellant, the ensuing pressure causes the burst disk to rupture and allows the combustion gases to flow across the surface of the orifice as the chamber vents. The vented combustor initiates a thermo-chemical-mechanical erosion process within the orifice that is similar to what a gun tube experiences upon firing. The test arrangement is shown in Figure 1.

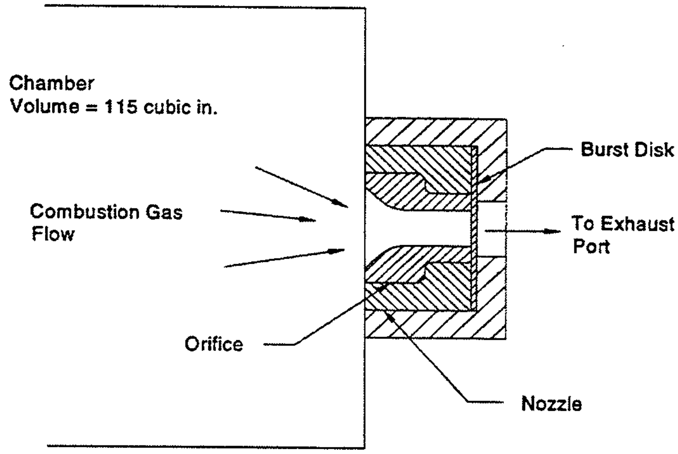

Figure 1. Schematic of vented combustor test setup.

This subscale method of testing obviously does not have the ability to precisely duplicate the environment of a large caliber gun during firing. The vented combustor was constructed as a single-ended enclosed tube used to test breech mechanism devices under pressures and temperatures that are comparable in order of magnitude and duration to those in a cannon. The objective of the testing is not to predict gun tube life, but to offer a lower cost method for comparing the high-temperature, thermochemical erosion performance of the experimental coatings, as opposed to costly live fire gun tests.

The specific test plan included an exposure of twenty firings per specimen, where a specimen represented a specific and unique combination of base metal, coating material, and coating application method. Each specimen was visually examined after each firing. After ten firings, each specimen was dimensionally inspected and photographed. Once testing was completed, the coated surfaces were again dimensionally inspected, photo-documented, and prepared for destructive evaluation. The propellant mass determination was performed by firing several shots on HC chromium baseline specimens. The intent was to establish a propellant mass that would cause substantial, but not total, loss of the HC chromium layer after twenty shots.

PROCEDURE FOR EVALUATING COATINGS

In order to identify potential candidate materials for gun bore application, one must consider the desired material characteristics of the coating. Some of the most important properties that must be taken into account when selecting a material system are:

- High melting point
- Thermal expansion coefficient of coating similar to substrate
- Adequate resistance to thermal shock.

The material systems selected for this study represent a new approach to coating technology and are therefore considered to be experimental.

Five potential candidate systems were identified for the study. These include three alloyed surfaces:

- Chromium selected due to its current use and favorable performance to date in gun tubes
- Tungsten-based and molybdenum-based alloys selected because of their processing characteristics and alloying properties with iron

The two other surfaces include:

- A composite surface, TiB_2, selected due to the excellent oxidation resistance afforded by the addition of boron
- An alloy/composite surface, Cr/CrB_2, selected due to the valuable properties of chromium, combined with the properties of diborides that provide a unique blend of erosion and corrosion resistance

Each of these material systems was laser surface alloyed (LSA) onto ASTM A723 low-alloy steel, in an effort to establish its baseline characteristics. The properties of greatest interest were material coating depth, adhesion, porosity, depth and primary metallurgical constituents of the heat-affected zone, and uniformity of coating. The LSA process resulted in a fairly rough (~12.5 µm/~500 µin.) surface finish, thus necessitating post-process machining. Typical gun bore requirements are a 0.40 µm (16 µin.) surface finish after electroplating. The LSA specimens were improved to a 3.20 µm (125 µin.) surface finish, using manual benching operations (i.e., filing, sanding, polishing). Concerns over total coating material removal halted efforts to further improve the surface finish.

RESULTS

Prior to testing, the overall surface condition of the orifice insert was visually examined and photo-documented. A representative photograph of the original surface condition of an unfired HC chromium coated insert is shown in Figure 2.

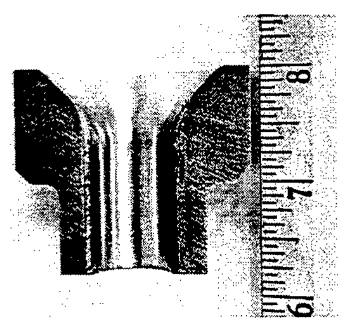

Figure 2. Unfired HC chromium coated specimen.

Figures 3 and 4 show the damage after twenty firings done to the HC chromium and LSA tungsten specimens, respectively.

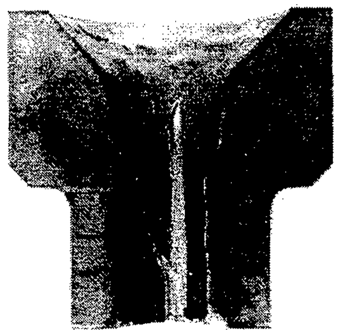

Figure 3. HC chromium coated specimen (twenty firings).

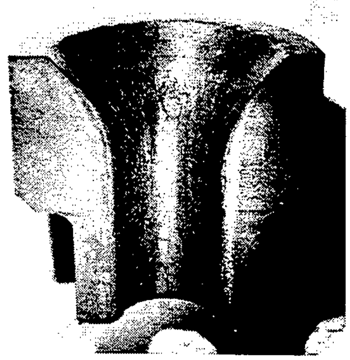

Figure 4. LSA tungsten coated specimen (twenty firings).

Dimensional loss measurements, obtained from a coordinate measuring machine are shown in Figure 5. The data reported starts 20.3-mm (0.8-inch) from the top of the orifice, which represents where the straight zone begins. The plot illustrates the average dimensional loss from HC chromium and bare (uncoated) steel specimens after ten and twenty firings. The hard chromium sample exhibited the lowest dimensional loss after the first ten firings; however, after twenty firings, a majority of the coating was stripped away from the surface.

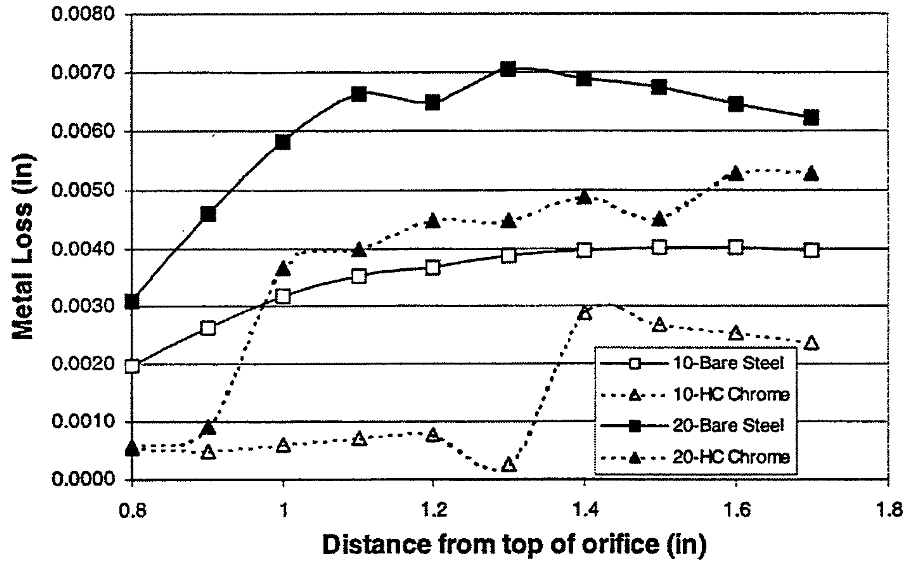

Figure 5. Metal loss (inches of depth) versus distance from the top of the orifice, showing comparisons after ten and twenty firings using average values for like specimens.

Dimensional loss measurements were also performed on the LSA specimens at the same intervals. However, due to the rough initial surface finish and the imprecision of the machining methods used, the data were purposely omitted. Metallographic examination of unfired LSA specimens identified complete coating removal had occurred in random areas during post-LSA process machining. The concern was that the data could be inaccurately interpreted when comparing the current production bore coating process to the experimental LSA process. The only LSA specimen that exhibited any remaining coating after twenty firings was the molybdenum specimen shown in Figure 6.

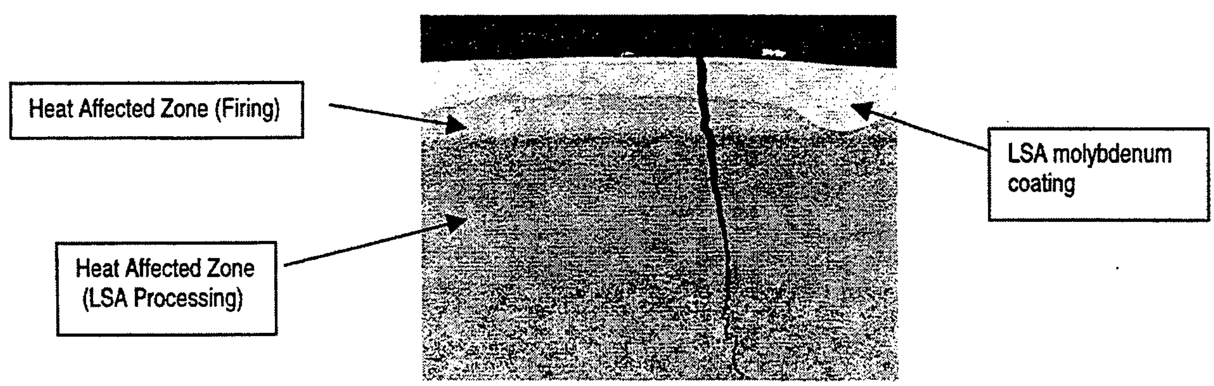

Figure 6. Micrograph of molybdenum specimen after twenty firings (50X).

The best method of characterizing the vented combustor to the actual gun tube environment is through analysis of the standard HC chromium layer and the underlying substrate involved in both instances. It should be noted that the same artillery cannon propellant that caused the full-scale damage was used in the vented combustor, although the mass used in the vented combustor was, not surprisingly, substantially less.

The inherent brittle nature of the hard chromium plating reveals cracks within the coating prior to exposure. The cracks form as a result of internal stress relief during coating deposition and the post-heat-treatment process (ref 2). The ensuing firing of hot propellant gases in the vented combustor exacerbates the cracking along the surface (Figure 7). The additional formation and subsequent progression of cracks into the base metal substrate are similar to those observed in a full-scale fired cannon (Figure 8).

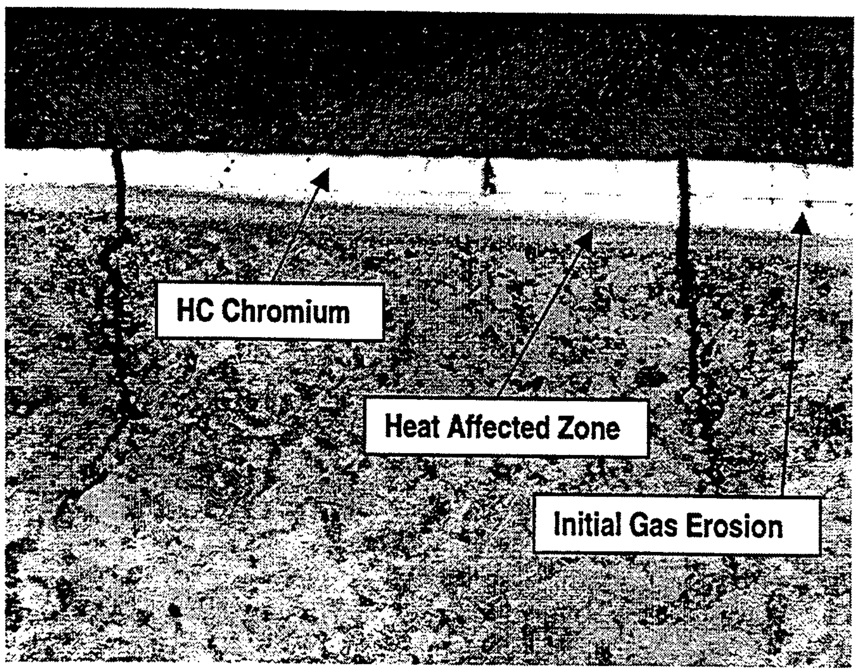

Figure 7. Damage to HC chromium in vented combustor after twenty firings (50X).

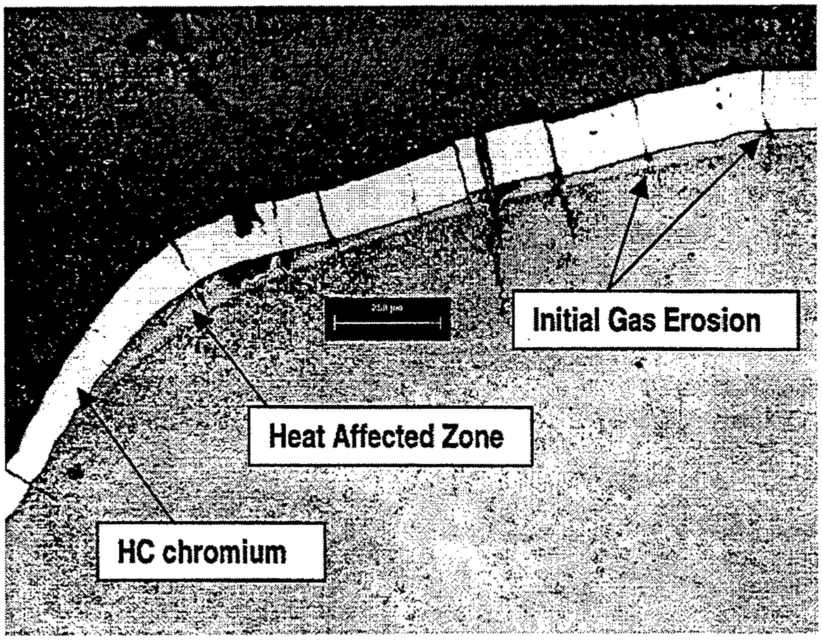

Figure 8. Damage to HC chromium in gun bore after 370 rounds (50X).

With repeated firing, the cracks penetrate the underlying base metal through the formation of erosion pockets, which eventually lead to deep cracks in the substrate (arrows in Figures 7 and 8). The resulting damage subsequently allows spallation of chromium plating from the substrate, thus exposing the bare metal surface. The high firing temperatures quickly form a heat-affected zone consisting of untempered martensite (formed when the steel is rapidly heated to above the austenitizing temperature and then is rapidly cooled), which is inherently brittle and provides a relatively easy fracture path. In addition, the mechanism that ultimately leads to HC chromium loss and subsequent coating failure is identical, i.e., loss of HC coating through adhesive failure. Crack progression within the substrate was intergranular in both the vented combustor and full-scale cannon, suggesting corrosive attack at the grain boundaries.

The primary difference between the two specimens, shown in Figures 7 and 8, is the transformation depth of the untempered martensite. The HC chromium vented combustor specimen indicates a transformation depth of 0.0095-inch, while the transformation in the gun tube sample is 0.0012-inch. It has been established, using one-dimensional heat-flow expressions, that the temperature at the gun bore (Figure 8) surface is approximately 1210°K (ref 3). The vented combustor specimen surface temperature was approximated to be 1350°K, using the same technique. The higher vented combustor temperature is one reason why the heat-affected zone was substantially deeper. Another characteristic that is distinctly different between the two systems is the duration of a firing impulse. The vented combustor firing cycle is 0.040 second in duration compared to a duration of 0.009 second in the gun system. The difference is attributed to the greatly reduced exit flow area of the orifice compared to a large caliber cannon.

This longer firing cycle for the vented combustor is another factor contributing to the deeper substrate transformation, as the steel is held above the transformation temperature (1020°K) for a longer period of time. Another contributing factor involves the velocity of the propellant gases. The velocity of the gases passing through the vented combustor orifice is much greater, simply because there is no projectile impeding combustion gas flow. The increased velocity causes a greater convection heat transfer coefficient in the vented combustor and ultimately results in a higher heat transfer rate (ref 4). There is also a substantial pressure difference between the two systems, whereby the actual gun system exhibits a greater pressure. Although pressure plays a role in the heat transfer rate, it has recently been shown that thermal shock effects, independent of other parameters, at ambient pressures can produce the damage seen in gun bores (ref 5).

CONCLUSIONS

Having identified these fundamental differences between the vented combustor and the actual gun system (i.e., temperature, duration of firing impulse, propellant gas velocity, firing pressures), it is important to note that the mechanism of erosion (chromium loss) is comparatively the same for both. The vented combustor is a much more aggressive test environment as compared to the actual cannon environment. The purpose of the vented combustor is not to create a one-to-one correlation with a cannon tube, but to provide a more economic means of testing coatings with simulated rather than actual shots, while maintaining comparative damage. Certain hardware modifications can be done to this specific vented combustor to shorten the firing duration, which would more closely replicate the thermal cycle environment in a cannon. One such modification involves enlarging the orifice diameter, which would increase the gas flow rate in the exit area. Impeding the gas flow velocity, as the projectile does in a gun tube, would be much more difficult to emulate.

Future work should entail using an interior ballistics code to model the inherent gas flow characteristics (i.e., velocity, temperature, pressure) of the vented combustor system. The model would provide a more comprehensive understanding of the combustion process within the vented combustor, such that modifications could be made that more closely replicate the actual firing scenario of a real gun tube.

With respect to coating performance, the nonuniformity of the LSA coating thickness and surface finish made comparative evaluation to HC chromium essentially impossible. The ambiguous nature of the material loss measurements leaves the authors with no technically sound basis for characterizing LSA coating performance. Further processing improvements, including a smoother "as-processed" finish and a more uniform coating thickness, would serve to reduce the need for post-process machining and thus potentially enhance the performance of this experimental coating technique.

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